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Workshop on Noninvasive Geophysical Site Characterization

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WORKSHOP ON NONINVASIVE GEOPHYSICAL SITE CHARACTERIZATION

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ABSTRACT

Workshop participants were asked to discuss DOE's needs for waste site characterization and the current status of noninvasive geophysical technology available to satisfy these needs. The initial discussions focused on electromagnetic, ground-penetrating radar, seismic, gravity, and magnetic methods. However, an additional technology, "data fusion" arose and was added to the list. The ultimate ranking of these technologies (i.e., in the order they would provide the most benefit to the DOE at the most sites, for the least cost, from top down) was as follows:

1. data fusion,
2. electromagnetic,
3. ground penetrating radar,
4. seismic,
5. gravity, and
6. magnetic.

1 EXECUTIVE SUMMARY

Workshop participants were asked to discuss DOE's needs for waste site characterization and the current status of noninvasive geophysical technology available to satisfy these needs. The initial discussions focussed on electromagnetic, ground penetrating radar, seismic, gravity, and magnetic methods. However, an additional technology, "data fusion" arose out of these discussions and was added to the list. The ultimate ranking of these technologies (i.e., in the order they would provide the most benefit to the DOE at the most sites, for the least cost, from top down) was as follows:

1. data fusion,
2. electromagnetic,
3. ground penetrating radar,
4. seismic,
5. gravity, and
6. magnetic.

Details of each method and its usefulness to the problem are discussed within the relevant sections that follow. A brief summary is provided here.

Data Fusion

Effective site characterization requires the utilization of several techniques and their multiple combinations in achieving the ultimate goal: finding and characterizing the environmental problem. One major recommendation: research methods of mapping, overlapping or combining, and viewing different data sets from geophysics, geochemistry, etc., in multidimensional space.

Electrical and Electromagnetic Methods (EM)

Attributes of an ideal EM system include high-density data, low cost, high resolution, wide applicability and ability to determine both real and complex resistivities. One major recommendation: obtain high-density data from remediation sites and demonstrate its value by using it in developing high resolution site characterization.

Ground Penetrating Radar (GPR)

Current GPRs offer the highest resolution of buried objects, but are limited in depth of penetration. They are affected by cultural clutter, and hampered by current signal processing and data interpretation methods. One major recommendation: improve antennas by increasing RF coupling to the ground using multistatic antenna arrays.

Seismic Methods

Long used in the energy exploration industry, advanced seismic methods only recently were applied to the shallow depths of interest in site characterization. One major recommendation: develop energetic high frequency (hundreds of Hz) seismic sources of both compressional and shear waves.

Gravity and Magnetics

These mature technologies did not seem as promising as the others. Specific recommendations focussed on further developing existing hardware.

Besides these technology reviews and recommendations, three issues of great concern often cited by workshop participants were:

- the "state-of-the-practice" versus "state-of-the-art" in geophysics,
- the difficulty of "fusion" of different survey data and results, and
- the decision-making process used in evaluating environmental problems and remediation.

These issues are all concerned with how better to use the technologies and data we already have rather than with how hardware can be improved.

2 INTRODUCTION*

A. WORKSHOP ORGANIZATION

Prior to cleaning up the more than 3,000 identified waste sites at DOE facilities, there is a logical and legal imperative first to characterize (describe) the sites as to their geography, type and degree of contamination, and their geology and hydrology. Sites are often characterized, in part, by drilling to gain information directly about the subsurface and its contents. Geophysics can provide methods for non-intrusive investigation of the subsurface at lower cost and with less risk to the investigators than drilling. Because of the immense size of the DOE characterization and cleanup program there is a perception that wider application of geophysical techniques would result in large cost savings and reduced risk to the health and safety of personnel. There is a further perception that existing geophysical techniques could be improved by judicious funding of research in select areas that might improve their current abilities to characterize waste sites.

Therefore, in order to provide DOE's Office of Technology Development (OTD) with expert guidance concerning research needs to improve non-intrusive geophysical characterization of waste sites, a workshop was organized and sponsored by OTD with assistance from Los Alamos National Laboratory and Ames Laboratory personnel. It was convened in Dallas, Texas, on August 29–30, 1991.

The workshop was charged with helping OTD in formulating a technology development plan for non-invasive geophysical technologies that would include:

- noninvasive waste site characterization needs,
- a catalogue of applicable technologies,
- an assessment (capabilities, limitations and data requirements) of each technology,
- identification of short-term and long-term technology improvements and technology developments required to meet characterization needs, and
- a comparison between technologies to prioritize research efforts in order to identify those areas of research that would provide DOE with the greatest return on investment.

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Participants in the workshop, mostly geophysicists, other scientists, and economists, were drawn from industry (16), universities (11), Federal agencies (10), and DOE Laboratories (21); their names and addresses are listed in Appendix A.

Following initial discussions among the participants it was mutually decided to consider the task in two stages. For the first stage, the participants divided into five groups, each being charged with carrying on in-depth discussions of a single technology. The five technology groups were:

(1) Data Fusion,
(2) Electrical and Electromagnetic (EM)
(3) Ground Penetrating Radar (GPR),
(4) Seismic, and
(5) Gravity and Magnetics

The first of these groups, Data Fusion, considered not a single technology, but aspects of collecting, integrating, and presenting geophysical and other data in order to make the planning of a geophysical survey and its results more productive and useful. The "technology groups," as they soon came to be called, carried on several hours of animated discussions before returning to report their recommendations to the workshop as a whole. At that time comments, corrections, and differing viewpoints were solicited from all. The technology groups were then reconvened to finalize their recommendations and prepare short reports on their findings. These reports make up Sections 3–7 of this document.

In the second stage of the workshop, participants were randomly divided into four "crosscutting groups."Each group considered the performance of all technologies for addressing three generic tasks common to most restoration sites:

(1) detection of objects, such as drums, buried at shallow depths (< 10 m),
(2) description and characterization of an area's local subsurface geology and hydrology, including such properties as stratigraphy, fracture extent and frequency, porosity, permeability, and water saturation, etc., and
(3) identification and tracing of plumes of pollutants in the subsurface.

The purpose was two-fold: (1) to rank the various technologies with regard to their applicability to the tasks; and (2) to identify and prioritize areas of research and development that would enable the technologies to perform these tasks better. Most of the groups began by deciding on the applicability rankings. Then each essentially devised its own approach to identify and rank the promising areas of research and development with respect to the expected pay-offs. The compilers of this report have combined the groups' results into three summary tables, one for each of the three generic tasks listed above. These tables appear in Section 8, page 27.

In order to meld the recommendations from the two phases of the workshop (the technology and crosscutting groups) the compilers began with the tables produced by each crosscutting group. These showed the ranking of each technology in relation to the three generic tasks described above. For those technologies that were indicated to be applicable or promising for addressing a task we then studied the report of that technology group to find the particular areas of research that needed stimulation. Because this job of comparing groups and technologies to arrive at overall recommendations is at least partly subjective, we asked the leaders of the groups to comment on our selections in the first draft, mailed out in mid-September, and then solicited comments and corrections on the second draft from all workshop participants. The finally agreed upon recommendations are summarized in the tables that begin Sections 3 through 7 below.

It had been our original intention to place cost estimates on the research areas identified as important. However, many participants were reluctant to do this without knowing more details of the required research. Consequently, all estimates of cost have been left out.

3 DATA FUSION (INTEGRATION)*

Data Fusion: Chapter Summary.

Effective site characterization requires the utilization of several techniques and their multiple combinations in achieving the ultimate goal: finding and characterizing the environmental problem. Data can be combined and manipulated in many ways so that the customer is oftentimes confused and has no roadmap as to the meaning of the composite results. The intent of data fusion is to combine data in such a manner as to provide the clearest possiblelogical picture to the customer. This probably means coupling the final results and all intermediate steps to a common computer imaging and geographic information system. Technology issues of note ("1" being the highest priority) appear to be:

Short Term (1–2 years)

(1) Promote the use of existing modeling techniques.

(2) Develop common format to improve data exchange among users.

(3) Establish a presentation methodology of greatest utility to users.

Long Term (3–5 years)

(1) Research methods of mapping and viewing different data sets from geophysics, geochemistry, etc., in multidimensional space.

(2) Research the physical and chemical properties of waste site contaminants and the products of reactions among them.

(3) Develop new modeling techniques such as coupled processes, full 3-D implementation of 2-D models, and others.

A. INTRODUCTION

Data fusion is the integration of several types of data (or evidence) to find a mutually acceptable solution to a problem. The topic encompasses more than just the discipline of geophysics. Data fusion should include all data that is acquired in the process of site characterization, including geophysics, geology, hydrology, geochemistry, civil engineering, and so forth. Some simple examples of data fusion exist in geophysics where two similar data sets are simultaneously inverted, such as gravity and magnetics, Menichetti and Guillen (1983), Serpa and Cook (1984).

The process of data fusion may be accomplished in several ways. A measurement results in a data point with an associated measurement error. When transformed into an equivalent space, several disparate measurements result in circles which may overlap. The locus of overlap may be considered an area of mutual agreement (or as a constrained solution to a problem). A more conservative approach would be to assume the solution is not in the overlapping area, but in the overall encircled area. Outlying circles may be assumed to result from errors (in measurement or interpretative assumptions), suggesting a second look at the data — or they may result from outlying possibilities (such as a hundred year flood event). The process of data fusion should be done in multi-dimensional space, and research is required into how disparate data sets can be transformed (or remapped) into a common problem space.

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B. RECOMMENDATIONS

Fusion of the data collected during a site characterization is impeded by

- lack of an evolutionary design and decision making strategy,
- problems with data related to quality, access, interchange, and management,
- poor understanding of physical and chemical properties and processes,
- failure to use existing theoretical and numerical models,
- ignorance of methods for data fusion and synthesis, and
- failure to realize necessity of presenting results for a variety of audiences to accomodate visualization.

These problems are discussed in more detail under the headings, 1. State of Practice, and 2. State of Art, below.

The GPR technology group has prioritized these topics in terms of short-term changes required in the state of the practice, and longer term research activities needed to advance the state of the art. These priorities are tabulated below in Table 1.

1. State of Practice

Under state of practice, most recommended research activities aim at ameliorating problems currently impeding not only effective fusion but also effective site characterization.

Evolutionary Design/Decision

To characterize a site effectively and efficiently, it is necessary to be flexible and allow the data gathering procedures to evolve as new findings change our understanding of a site. This evolutionary approach requires that data be evaluated as it is gathered so that the next step in data acquisition may be modified to take full advantage of the earlier findings. The bureaucratic process often impedes this through contract/procurement practices that are overly detailed and specific.

Modeling

There are many theoretical and numerical models that are not commonly being used at the state of the practice level. These models are useful as aids in interpretation, prediction of successs for a technique at a site, and verification of an interpretation. Practitioners need to be educated in their availability and use.

Data Issues

To work successfully with a variety of data sets, it is necessary to be able to access the data, read it once accessed, readily manipulate it, and have confidence in the quality of the data. Access is often impeded simply by lack of knowledge of the existence of the data, and, in the case of DOE facilities, by the requirements of classified facilities, information, and data. Reading the data, once accessed, requires knowledge of the formats in which the data are stored. This matter is best accomodated through standards of data interchange that are widely accepted and used (mandated). Once read, appropriate software tools are required to readily manipulate large data sets.

Visualization

Finally, the state of the practice must become accustomed to presenting the results of site characterization at a variety of levels. At the technical peer review level, scientific visualization will demand a minimum of filtering of the technical content of the data, modelling, and interpretation. At the level of public comment and legal review, the same information must be filtered to a more pictorial presentation level for concise communication and explanation of the essentials.

2. State of Art

Some of these same issues must be advanced at the state of the art level, and then transferred to the state of the

Table 1. Research priorities.

	State of Practice	State of Art
1	Evolutionary design-decision	Fusion and synthesis
2	Modelling	Physical/chemical properties/processes
3	Data issues	Modelling
4	Visualization	Visualization

practice, while others must be addressed at the state of the art level to advance the state of knowledge.

Data Fusion

The process of fusion itself requires considerable research. How do we map disparate data sets from geophysics, geochemistry, hydrology, and so forth, in a multidimensional space, into some space where intersections of commonality may be found (e.g., to find a consistent solution to the problem)? What kinds of statistics should be used? What levels of confidence are required?

Physical/Chemical Properties

There is a fundamental gap in our knowledge of the physical and chemical properties of many contaminants and of the processes that occur *in situ* at contaminated sites. Of the USEPA top 100 contaminants, one third exist only at hazardous waste sites — they are the products of reactions among the original contaminants and have never been manufactured for any purpose. Therefore, their properties are unknown, Lucius (1990). Many of the processes that formed these materials, as well as the processes of reaction between these materials and natural ones, are also unknown.

Modeling

Though many theoretical and numerical models exist and should be transferred to routine use at the practice level, there are many models that are still needed— especially models of coupled processes, full 3-dimensional models, and statistical models of heterogeneity.

Visualization

There is also a need for better multidimensional, scientific, visualization tools, including animation tools to allow the study of 3D data as a function of time (4D).

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4 ELECTRICAL AND ELECTROMAGNETIC METHODS (EM)*

EM Technologies: Chapter Summary.

Attributes of an ideal EM system include high density data, low cost, high resolution, wide applicability and ability to determine both real and complex resistivities. In priority order, development needs are:

Short Term (1–2 years)

(1) Develop enhanced data processing and graphical displays and interpretation for ease and flexibility of use by investigator and customer. Images should be interpretable by both user and customer in order to enhance the customer's understanding of what the survey is detecting and what it is capable of. Develop capability of forward modelling and 3-D display which will aid in the design of surveys and in addressing the survey's applicability to a specific site.

(2) Obtain high density data from remediation sites and demonstrate its value by using it in developing high resolution site characterization.

(3) Develop methods to filter cultural interference to permit electrical and electromagnetic methods to be used in areas of high cultural noises, such as most DOE sites.

(4) Research enhanced systems that include flexible spectrum to fill the gap from 10 kHz to 2 MHz, and that also measure conductivity, dielectric constant, and time of flight (the travel time of a ray along a ray path analogous to seismic systems). Such systems would provide flexibility of equipment so a survey could be tailored to any site. Thus, the need to use multiple systems for a single study would be avoided. Overall lower costs would therefore result.

Long Term (3–5 years)

(1) Study chemistry and electrochemistry that effects electrical properties of geological systems including fluid-rock interactions, biological effects and contaminant reactions.Such knowledge will allow more rigorous approaches to quantitatively determining hydrologic properties from electrical properties.

(2) Research ways to recognize and remove cultural noise to permit electrical and electromagnetic methods to be used in regions of high cultural noises.

(3) Enhance system capabilities, especially in the frequency range of 10 kHz to 2 MHz, to permit both resistivity and dielectric constant to be measured.

(4) Develop a sound theoretical and model basis for interpreting the various sources that give rise to self-potentials.

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A. Introduction

1. Basis and Application to Hazardous Waste Sites

The wide variety of electrical and electromagnetic methods used in geophysical studies fall into two broad categories, those which are used to infer the electrical conductivity of the ground, and those which measure natural electric potentials produced by a variety of subsurface flow processes. The first category includes the techniques of resistivity, induced polarization (IP) and electromagnetics (EM), the second, self potential (SP).

The electrical conductivity of most soils and rocks depends entirely on the conduction paths afforded by fluids in the pore spaces. It is determined by the porosity, saturation, pore fluid salinity and clay content. Because conductivity is influenced by the dissolved solids in groundwater, mapping it may be the only direct detection method for high concentrations of contaminants that form ionic species. In most applications, however, the role of electrical conductivity is to assist in characterizing a site, a task which includes not only specifying the location of contaminants but mapping the physical and chemical properties of the ground that control their distribution and movement. In the most general sense, mapping electrical conductivity is important for conditioning or constraining the hydrological models of contaminant transport and retention. These models are usually based on drill hole tests and suffer from the problem of extrapolating point measurements made at infrequent drill holes to the volume between the holes. The difficulty in relying solely on drill hole studies is illustrated by the problem of a channel of high permeability sand that has been missed in by a drill pattern. There is no reliable way to predict the fast path properties of this channel from the drill hole measurements, and yet this channel would be the dominant feature of the site in terms of contaminant transport. Mapping the subsurface distribution of electrical conductivity would reveal the geometry of the subsurface property distribution, and could drastically change the hydrologic model.

At the majority of impacted sites, waste sources are buried in unconsolidated sediments (soils) and migrate into and move with the groundwater. The rates and pathways of this migration are strongly influenced by clay content and clay mineralogy. The presence of clay not only increases rock conductivity, but it brings about a distinctive frequency dependent conductivity known as the induced polarization (IP) effect. This important property has been little used in hazardous waste studies and yet it relates directly to clay content and chemistry of the pore fluids both of which are essential for site characterization.

The resistivity, IP, and EM methods that have been used in shallow studies use either quasi-dc methods (where induction effects are negligible) or low frequency methods, where low is taken to mean frequencies in which conduction currents are greater than displacement currents. For most sedimentary rocks and unconsolidated soils and sediments, conductivities are greater than 10^{-2} and the dielectric constant, which is dictated by the water content, is unlikely to exceed 50. In these conditions, the displacement current, or dielectric effect, is insignificant for frequencies less than 100 kHz. The ground penetrating radar methods discussed in the next section use frequencies in the MHz range where the response is controlled by water content as well as conductivity, but the penetration is severely limited by attenuation (skin depth). Conventional EM systems are not presently capable of operating between 100 kHz and a few MHz despite the obvious usefulness of this band for shallow contaminant studies.

Metallic objects, such as buried drums, also give rise to anomalies in electrical and electromagnetic methods. (Near-surface metallic conductors also give rise to unwanted anomalies that obscure anomalies from deeper targets). Electromagnetic methods are suitable for detecting such features. An extensive literature exists for metal locators, but there has been very little qualitative analysis of the systems best suited for hazardous waste targets, nor has there been any systematic effort to study the means to eliminate unwanted surface anomalies through filtering, adaptive cancellation, etc.

The natural dc electric potentials often called SP (self potentials or spontaneous polarization), are manifestations of coupled flow phenomena. Basically, driving forces of temperature, hydraulic pressure gradients, chemical potentials, and voltage gradients produce flows of heat, fluid, chemicals, and electric current. These flows are coupled in the ground in the sense that not only does a pressure gradient produce a fluid flow but it also produces a current flow, the streaming potential. Similarly, temperature gradients drive currents to produce thermoelectric effects. Concentration gradients produce the familiar SP anomalies in drill hole logging especially in the presence of clay which acts as a selective filter for certain ions and greatly enhances the voltages produced. It is likely that similar effects are involved in producing the voltages measured in SP surveys but surprisingly there has been very little study of this phenomenon. The importance of streaming potentials in shallow fluid flow studies is well recognized. Fluid flow in a porous medium generates an electric field. The field depends on the driving pressure, rock permeability, electrical conductivity of the fluid, and the electrical properties of the mineral surfaces past which the fluid flows. Leakage of fluids from lined ponds and natural flows along faults give rise to measurable electric fields on the surface.

Another cross-coupling effect with potential utility in contaminant studies is electro-osmosis, a flow of fluid produced by a voltage gradient. This phenomena has been used in geotechnical engineering applications to stabilize embankments and assist in pile driving. It has practical value as a means for altering subsurface flow patterns by directing a particular contaminant plume to an extraction or treatment region. Since the effect depends on fluid conductivity, rock permeability and the configuration of the imposed voltage gradients, the site must be well characterized in the first two properties before the design of a practical system could be implemented.

The importance of electrical conductivity seems to be well recognized in hazardous waste studies and many articles on the relationships between conductivity and groundwater contamination have appeared in the hydrology and geophysics literature. However, by and large, the level of sophistication in measuring conductivity as exhibited in published studies falls short of that achieved in other areas of application. For example, in IP, sophisticated measurement techniques and effective interpretation schemes, including inversion, have been developed for mineral exploration. Nor has the application of SP in the hazardous waste area proceeded very far beyond relatively crude measurement of first order streaming potentials from leakage paths.

2. Description of State of the Practice Surveys

In principle, the measurement of SP is the most straightforward of the electrical methods. In practice great care must be taken to reduce the voltages and to filter out a certain base level of noise from the electrodes. A thorough review of the SP method is presented by Corwin (1991) and he includes several references to the use and potential application of SP in hazardous waste studies. As in the other electrical methods, there is a fundamental problem in relating measurements made on the surface to the sources (or electrical conductivity) at depth. Despite some strong progress in modelling, the interpretation of SP anomalies is in a relatively early state of development.

The determination of electrical conductivity is also simple in principle. A current is induced to flow in the subsurface either by direct injection through grounded electrodes or by induction by a time varying magnetic field. Electric or magnetic fields measured at a point on the surface are used to infer the distribution of current, and hopefully conductivity, in the subsurface.

In the dc or IP techniques low frequency ac is actually used with the proviso that the induction effects are negligible. Current is injected between two electrodes and another pair is used to measure the potential drop associated with the current. If the subsurface is horizontally stratified, a sounding of the section is made by widening the separation between the surface electrodes. If the section is known to be inhomogeneous, combinations of sounding and lateral profiling configurations are used. A tutorial review of resistivity and IP methods has recently been presented by Ward (1990).

Electromagnetic methods employ a very wide range of configurations. The sources can be either wire loops or grounded wires and both electric and magnetic fields can be measured. The measurements can be conducted in the frequency domain or in the transient or time domain. In principle, the electromagnetic methods should provide higher resolution of subsurface features than the dc methods, but surprisingly there are no rigorous definitions of the advantages of one configuration or technique over another. The effective depth of exploration for these controlled-source em systems can be varied by changing either the spacing between transmitters and receivers or the frequency for a fixed configuration. A definitive work entitled "Electromagnetic Methods in Applied Geophysics—Theory" has recently been published by the SEG (Nabighian, 1989) and a companion volume on applications details the state-of-the-art in the various configurations that are used. A more specialized review of electromagnetic methods for groundwater studies is presented by McNeill (1990). Again it appears that with a few notable exceptions the state of the practice in hazardous waste site characterization lags behind the state of the art that has evolved for other applications.

Regardless of method used to measure electrical conductivity, the interpretation of data taken in inhomogeneous media is the major challenge. Sections made up from one-dimensional inversions of data at widely separated points is often the norm. Some limited success has been achieved for two-dimensional inversion of resistivity and IP profiles but there are as yet no such algorithms for controlled-source EM. In 3-D geology there are no practical forward EM models for arbitrary conductivity distribution so quantitative interpretation of EM data tends to be qualitative. There is general recognition of the need to increase the density of measurements, but as yet, there are no criteria for station spacing, frequency bandwidth or even configurations that optimize the mapping of a particular feature. Finally there is a very great need to present the survey results in images or maps to make these surveys useful to the site engineer or hydrologist.

A great challenge for geophysists is to come to a common definition of resolution. The quantitative demands of hazardous waste site characterization will require precise definition of resolution and sensitivity so that uncertainties in the interpretation can be defined for regulatory and legal purposes. These requirements must drive some basic theoretical/numerical studies to quantify the geophysical measurements in completely new ways. The tools are now available for such studies, but very few groups are engaged in this work.

3. Approach of the Electrical and Electromagnetic Working Group

The team evaluating electrical and electromagnetic methods at this workshop attempted to (1) define an ideal electrical and electromagnetic approach, (2) specify short term (1–2 years) and long term (3 –5 years) research and development required to approach the ideal system, and (3) identify the methods most applicable to generic characterization needs for a waste site—the needs being object detection, geologic/hydrologic description, and detection and mapping of pollutant plumes.

We view the separate electrical and electromagnetic methods as points on a spectrum of methods that measure electrical conductivity; therefore, we will discuss their development as one entity. Our basic conclusions from this evaluation are:

- Electrical and electromagnetic methods are powerful but underutilized techniques for waste site characterization.
- A significant step in the application of electrical and electromagnetic methods to waste sites is the research needed to quantify the relationship between electrical properties and hydrogeochemical processes occurring at such sites.
- There exists a huge gap between the state-of-the-art and state of the practice for EM methods.
- The methods have been traditionally used on the surface, but there are important gains to be made using borehole-to-surface and borehole-to-borehole methods.
- There is an important band from 100 kHz to several MHz which should be used for shallow studies and which would involve indirect measurement of dielectric constant.
- An increased adaptability of these methods to different geologic and electrical environments can be gained by adding capabilities to correct for cultural interference, to utilize different frequency bands, to switch from time domain to frequency domain, and to obtain multiple components of the electrical and magnetic field.
- A major need is to better tailor the electrical or electromagnetic survey to the needs of the ultimate user during site remediation. This customizing can be accomplished by a thorough representation to the user of the resolution and limitations of the survey, stronger pretest modelling and survey design that is comprehensible to the nongeophysicist, and presentation of the survey results in a format digestible by practitioners of other disciplines working on the project.
- There is a need for faster and easier to use 2-D or 3-D forward models to both design experiments and to assess the basic limits on resolution.
- There must be rapid development of imaging or other interpretation procedures especially in 2- and 3-D situations to make the geophysical studies useful to the site engineers.
- In general, there is a need for several well characterized test sites to validate these methods for environmental and hazardous waste studies.

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5 GROUND PENETRATING RADAR (GPR)*

Ground Penetrating Radar (GPR): Chapter Summary

Although current GPRs offer the highest resolution for shallow investigation,they are limited in depth of penetration, are affected by cultural clutter, and are hampered by current signal processing and data interpretation methods. Immiscible hydrocarbon contaminants have also been detected directly by GPR. Research priorites are:

Short Term (1–2 years)

(1) Improve radar signal processing to reduce clutter from above an below ground cultural features.

(2) Use signal stacking, data migration and synthetic aperture radar processing to clarify images.

(3) Evaluate advanced GPRs recently developed at several agencies, analyze their performance characteristics and incorporate such features in improved GPRs.

(4) Improve forward models for target recognition.

Long Term (3–5 years)

(1) Improve antennas by increasing RF coupling to the ground using multistatic antenna arrays.

(2) Improve data acquisition hardware, e.g. incorporate complete RF waveform recording to shorten surveying times.

(3) Develop data base of the physical and chemical properties of contaminants to aid detection of subsurface contaminant plumes.

A. INTRODUCTION

Ground penetrating radar employs an extremely short electromagnetic pulse that penetrates the earth. A small portion of the pulse energy is reflected off subsurface discontinuities back to the surface. The return signal is continuously recorded for a short duration on a strip-chart or, in some case, into a digital recording device. Amplitude of the reflected pulse is related to changes in electrical properties in the subsurface. Such changes primarily reflect differences in bulk density and water content, with lesser contributions from fluid and mineralogical compositions. The water table is an obvious reflector in coarse grained sand (but not so obvious in fine sand or till due to the more difuse capillary fringe). As the electrical properties vary with density and water content as a power law, very subtle changes in porosity may be mapped (reflecting sedimentary structures). The large chemical reactivity and small particle size of mineralogical clay, such as montmorillonite, produce radar barriers, severely limiting depth of penetration in mineralogical clay soils, but not in soils containing clay size material such as rock flour. GPR

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anomalies from a man-made structure, such as a waste pit, result mostly from artifical geometric shapes of buried targets. These targets may include both metallic and non-metallic objects such as drums, pipes, concrete blocks, bulk chemicals, etc. Under favorable geologic conditions, the method can also detect disturbed soils and backfills.

Current GPRs have the following limitations when applied to waste site characterization:

- Limited depth of penetration/resolution caused by signal attenuation by conductive geologic media.
- Sensitivity to geologic and cultural "clutter".
- Sensitivity to antenna ringing.
- Data interpretation methods are often not adequately quantitative or designed for the human interface.
- Lack of data on physical and electromagnetic properties of soils and contaminants.

GPR improvements can be divided into the following general categories, rank ordered with respect to their likelihood of alleviating the limitations listed above.

1. Signal processing
2. System hardware
3. { Data interpretation
   EM property measurements
4. Forward modelling development

The discussion below provides detail on the improvements that could be expected from advancing the particular technology area.

B. SIGNAL PROCESSING

The signal processing area encompasses many topics. The items placed in this category include any type of signal analysis/enhancemnt which would make GPR data more amenable to interpretation. Such processing is primarily of an image-improvement nature which would neither eliminate information nor be biased toward a specific interpretation requirement.

At the present time the majority of GPR data displays simply show the raw data as recorded from the instrument. While some enhancement is being applied and some state-of-the-art demonstrations of the application of seismic processing to GPR have been reported, a major effort is needed to bring these processes to the point where they can be routinely applied to GPR data. The simple step of storing data in SRG-Y format has already facilitated use of commercial PC-based seismic software packages. Although GPR and seimic data look the same, they are not, so standard seismic processing can be misleading.

The key objectives of signal processing are:

1. reduction or elimination of "cultural clutter" from above ground radar scatters;
2. reduction of "geologic noise" or "geologic clutter," but with the recognition that one man's signal is another man's noise;
3. application of image clarification processes, variously referred to as multifold seismic-style data acquisition, stacking, and migration, multistatic or synthetic aperture radar (SAR) processing;
4. generation or adoption of data presentations which facilitate interpretation and ease of end-use;
5. integration of as many of these processes as possible in the field for on-site data assessment.

The general consensus of the group was that this area of research would yield the maximum return on R&D investment in the short term (1–2 years).

C. SYSTEM HARDWARE

Advances in GPR technology aim at increasing depth penetration and target resolution, overcoming problems associated with geological "clutter,"and reducing survey times. Research will involve modifications to current systems as well as prototyping wholly new GPR systems.

1. Antennas

One main area of hardware enhancements involves antennas. New antennas having increased RF coupling to ground will increase system dynamic range and allow for greater depth of penetration. Further reduction of antenna ringing is essential because such ringing can obscure weak scatterers. Reducing cultural clutter and surface crosstalk will also increase system performance. Use of multistatic antenna arrays combined with signal processing such as SAR and beam-shaping techniques may yield increased depth penetration and resolution. Overall inputs to antenna performance will in turn yield improvements in GPR system performance. If the antennas can be lifted off the ground, surface area coverage per unit time can be increased and GPR can be applied in more difficult terrains. Finally new antenna designs that differ from those commercially available need to be researched.

2. Signal Acquisition Hardware

If signal acquisition hardware is improved, area coverage time can be decreased. For example, if complete RF waveform recording is applied to current pulsed type GPRs data collection time is reduced.

3. State-of-the-Art GPRs

Several state-of-the-art GPRs, whose performance outstrips those in daily field use, are under development at various agencies and laboratories. Some have already implemented the various improvements listed above. Others incorporate CW-type radar rather than pulsed radar. Performance characteristics of the new GPRs should be analyzed and if applicable be brought to "state-of-the-practice."

D. DATA INTERPRETATION

Current GPR data processing procedures are largely based on visual inspection of data displays. This is an inherently subjective process that relies upon the experience and commitment of the analyst. An initial interpretation of the data is visually performed during the data collection process. This permits the operator to monitor the operation of the GPR system and to make an identification of at least some of the major subsurface features that might be present. A more detailed laboratory-based interpretation process is required following data acquisition.

At either stage, advanced data processing algorithms, including target recognition algorithms, are needed to assist the analyst. Filtering, clutter removal, and feature enhancement/recognition combined with advanced video display capabilities will help to minimize the subjective aspect of the interpretation process and will enhance the cost effectiveness of the GPR method. Stereo and 3-D displays will give the analyst a dramatically improved ability to visualize subsurface structure of the surveyed volume.

E. PHYSICAL PROPERTIES OF CONTAMINANTS

GPR has the potential to directly detect contamination (both organic and inorganic) in the subsurface with fairly high resolution. A data base of the physical and chemical properties of the contaminants is needed to predict such response. A detailed literature search conducted by the USGS, funded by the EPA (EMSL-LV), indicated that many of the properties needed for a geophysical evaluation have not been measured. In addition, many of the contaminants interact with the geological minerals and with each other. These interactions may affect a GPR response. Completion of a database of priority contaminants is recommended with laboratory measurements. The next phase would be testing at a controlled field site to evaluate the levels of detection possible under different geological environments (e.g. fractures, clay horizons, etc.). It is recommended that joint federal government agencies (DOE/EPA/DOD/DOI) establish a number of undisturbed clean sites of different geology where contaminants can be injected into the subsurface and geophysical measurements obtained before, during, and after injection. Such experiments have been done at one type site at the Canadian Forces Base Borden, under direction of scientists at the University of Waterloo. These laboratory data and field experiments would be beneficial for the GPR, electromagnetic, DC resistivity, and complex resistivity methods as well as a number of borehole techniques.

F. FORWARD MODELING

Computer models are available for one and two dimensional models.. The model for a simple 1-D structure can be approximated by two antennas separated by twice the transmitter-target distance. An integral equation solution for this antenna pair can be used to determine the pulse generated at the receiver in a homogeneous medium. This is then modified by the reflection coefficient at the interface.

However, this model needs to be improved to include multiple layers and for the case where 2-D anomaly is not parallel to the surface.

The case for 3-D anomalies needs to be set up in a more general fashion. The target in this case needs to be treated in the more general radar cross section analyses prevalent in aircraft scattering. These would include geometrical optics, physical optics, asymptotic techniques, integral equation and finite difference and finite element solutions.

G. SUMMARY

GPR currently has two primary applications toward environmental recovery efforts at DOE sites: (1) Identification and location of objects buried beneath the surface and (2) identification and location of contaminant plumes. It is believed that the greatest advances in these techniques can be gained in the following issues:

- Data interpretation
- Penetration depth/resolution
- Geologic noise (clutter) limits
- Area coverage per unit time
- Acquire physical property information.

The area of concentration which is likely to yield the largest reward or return on investment is improvement in data interpretation.

Recommended Technology Advances

I. Signal Processing
  - a. Reject clutter
  - b. Improve human interface
  - c. Extract physical properties
  - d. Real time processing

II. Antenna Development
  - a. Increase mobility
  - b. Coupling efficiency
  - c. Clutter & interference rejection
  - d. Multistatic
  - e. SAR processing
  - f. Improved antennas (crosstalk, ringdown ...)

III. Target definition
  - a. Develop test site
  - b. Test program for specific targets
  - c. Effect of contaminant on geologic properties
  - d. EM database for EPA listed contaminants
  - e. Theoretical analysis of target signatures

6 SEISMIC METHODS*

Seismic Methods: Chapter Summary

Long used in the energy exploration industry, advanced seismic methods are now being applied to the shallow depths of interest in site characterization. The heterogeneous nature of near-surface materials makes data processing difficult, but the shorter wave travel distances mean that higher frequency seismic waves, offering greater resolution can be transmitted, and in some cases, shear waves can be analyzed to yield greater information.

Short Term (1–2 years)

(1) Develop energetic high frequency (hundreds of Hz) seismic sources of both compressional and shear waves.

(2) Adapt faster microprocessors and pulse-coded recorders for real time processing of stacked data.

(3) Develop nine component vertical seismic profiling, including shear wave analysis.

Long Term (3–5 years)

(1) Develop cross-hole, nine component shear wave tomography.

(2) Improve multicomponent seismology for detecting fractures.

(3) Develop transposed vertical seismic profiling methods, wherein seismic sources are located in boreholes directionally drilled under waste sites.

A. BACKGROUND

Seismic methods have roots that go back to the early part of the 20th century. The seismic-reflection method in particular is a powerful geophysical exploration method that has been in widespread use in the petroleum industry for more than 60 years. Substantial progress has been made in all of the seismic methods in the past 20 years. The revolution in microelectronics has resulted in construction of engineering seismographs and microcomputers for data collection and processing that now permit the cost-effective use of seismic methods in a wide variety of environmental applications. The current state of the art is quite advanced and in our opinion underutilized in hazardous waste site characterization studies. It is important to note that the "state of the art" and the "state of the practice" are often quite different.

Seismic methods measure the elastic and acoustic parameters of the subsurface, and require careful attention to avoid possible pitfalls in data collection, processing, and interpretation. It is important to carefully plan seismic surveys around the geologic objectives and the resolution limits of the technique. Careful planning is also necessary to make the method increasingly cost effective relative to test drilling and/or other geophysical methods. The selection of seismic energy source, recording equipment, and data-acquisition parameters are often critical to the success of shallow seismic projects. As resolution improves and cost-effectiveness increases, new applications will be found. These will be evolutionary processes, as the seismology group forsees no revolutionary new techniques, processing, equipment, or display procedures.

Seismic methods are most sensitive to the mechanical properties of earth materials and are relatively insensitive to their chemical makeup and contained fluids. Electrical methods, in contrast, are sensitive to contained fluids and to the presence of magnetic or electrically conductive materials. In other words, the measurable physical parameters upon which seismic methods depend are quite different from the physical parameters measured by electrical and magnetic methods. This argues for collection of multiple data sets by a variety of techniques for a complete description of waste sites (fluids, stratigraphy, etc.).

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The principles of sound waves apply to P-waves, which are compressional waves; P-wave reflections can be thought of as sound wave echoes from underground. P-waves propagating through the earth behave like sound waves propagating in air. When a P-wave meets an acoustical contrast in the air or underground, echoes (reflections) are generated. In the subsurface, however, the situation is more complex than in air because some of the energy incident on a solid acoustical interface is transmitted across the interface or converted into useful refractions and/or shear waves. While seismic reflection methods and ground-penetrating radar are similar in concept, (both methods use reflections of energy from underground features), they are almost mutually exclusive in terms of where they work well. Radar works well in the absence of electrically conducting materials near the earth's surface, but will not penetrate into good electrical conductors. Seismic reflection, on the other hand works best where the water table is near the surface and easily penetrates damp clays that are excellent electrical conductors. Radar penetrates dry sands that will not easily transmit high-frequency seismic waves.

B. SEISMIC METHODS RELEVANT TO ENVIRONMENTAL PROBLEMS

It is not the purpose of this discussion to present a thorough explanation of exploration seismic methods. It is important for the reader to know, however, that certain similarities exist among the various seismic methods, and what the general limitations of the methods are. In all seismic methods, some source of seismic energy is used and some type of receiver is needed to detect the seismic energy after it travels through some volume of the earth. In this report we will assume the use of geophones as receivers except where we explicitly mention hydrophones or accelerometers.

1. Seismic refraction

The seismic refraction method requires that the earth in the survey area be made up of layers of material that increase in seismic velocity with each successively deeper layer. The data analysis becomes more complicated if the layers dip or are discontinuous. The requirement for increasing velocity is a severe constraint for many shallow applications where low-velocity layers are often encountered within a few meters or tens of meters below the earth's surface. For example, a sand layer beneath clay in an alluvial valley commonly has a lower seismic velocity than the clay, so seismic refraction has limitations in such a situation. The technique is cheap and often cost-effective in those cases where it can be applied. An excellent paper by Lankston (1990) discusses modern refraction techniques, including the generalized reciprocal method (GRM). Other relevant references include Lewis and Haeni (1987), Scott et al., (1972), Palmer (1980), and Zohdy et al., (1974).

2. Seismic borehole tomography

Tomographic surveys use the same mathematical approach that has been so successfully used to compute three-dimensional images of the human body using x-ray data (computed axial tomography or CAT scan). In seismology the technique depends on measurement of travel times for large numbers of seismic ray paths through a body of earth material. While the technique involves timing ray paths between boreholes, it is common to time surface-to-borehole and/or borehole-to-surface ray paths also. The technique is computationally intensive, and is costly because of the need for boreholes. It often gives a very detailed attenuation and/or velocity model between the boreholes. Tomography has been used to study the interior of the earth from scales of thousands of km to tens of meters (Humphreys et al., 1984; Clayton and Stolt, 1981).

3. Vertical seismic profiling (VSP)

This technique, seldom used by itself, facilitates better interpretation of seismic reflection data. It is commonly done with a string of hydrophones, 3-component geophones or 3-component accelerometers in a borehole and a surface seismic source located within a few seismic wavelengths of the borehole. It allows accurate determination of one-way travel time through successive geologic units. It also allows analysis of attenuation and acoustic impedance which are needed for construction of synthetic seismograms. The synthetic seismograms are then used for comparison with seismic-reflection data to identify specific geologic formations and to refine depth estimates of those formations.

A significant use of VSP in igneous and metamorphic terrane is the detection, location, and assessment of effective permeability of productive fractures that intersect a borehole. References on VSP include Galperin (1974), Balch and Lee (1984), and Hardage (1983).

Transposed VSP involves the use of a source located in the borehole and receivers, usually geophones, located at the earth's surface. Transposed VSP has the advantage of being faster and cheaper to perform, provided a suitable seismic source can be placed in the borehole and used repeatedly at different depths without destroying the borehole.

4. Shallow seismic reflection

The seismic reflection technique involves no *a priori* assumptions about layering or seismic velocity. However, no seismic energy will be reflected back for analysis unless acoustic impedance contrasts (i.e. density or velocity differences) are present within the depth range of the equipment and procedures used. The classic use of seismic reflections is to image subsurface stratigraphy and structure. The technique can also be used to search for anomalies such as isolated sand or clay lenses. The technique is rapidly becoming more cost-effective which encourages new applications. Resolution is also improving. Steeples and Miller (1990) provide an overview of seismic reflection as applied to shallow exploration problems.

C. DEEP VERSUS SHALLOW REFLECTION SEISMOLOGY

Deep reflection seismology has been heavily utilized for more than 60 years in the petroleum industry for the purpose of identification and definition of subsurface structures. It has been neglected in the environmental industry due to its high cost and relatively low resolution. However, it may be the technique of choice when it is desirable to characterize the regional geology of a site or facility. Several of the the facilities in the DOE complex are located in tectonically disturbed areas. Deep seismic surveys can contribute to the understanding of a site's stratigraphy and structure and may provide information on how structure influences contaminant migration.

High resolution reflection seismology has been defined by Sheriff (1991) as containing dominant frequencies of more than 80 Hz. Shallow high resolution reflection seismic surveys have proven useful in identifying subsurface channel sequences in both alluvial and bedrock material as well as delineating the alluvial-bedrock contact. This technique allows the hydrogeology of a site to be characterized with a minimum of boreholes.

D. WHY ARE SEISMIC METHODS NOT USED MORE WIDELY?

Several factors have prevented surface seismic methods from being the "technique of choice" in typical environmental investigations. Until the past five years the techniques, particularly seismic reflection, have been prohibitively expensive. This is changing with the recent advent of a new generation of seismographs, cheaper software, and microcomputers which have combined to decrease the cost of field work and data processing. Acquisition and recording systems with acceptable dynamic range and broad bandwidth are now available to record the high frequencies necessary for shallow reflection work.

The refraction method has been used in engineering and geotechnical investigations for several decades. The reflection method, on the other hand, was not adapted to use shallower than 30 meters until the mid 1980s. It is now possible in some cases to use seismic reflection at depths as shallow as 2 meters, but these new capabilities are not yet widely known, especially outside the relatively small but growing community of environmental geophysicists.

Attenuation tends to be very high in shallow media, particularly in arid regions with water tables deeper than 10 meters. In many areas, the acoustical impedance contrast is not strong enough at stratigraphic boundaries to produce recordable seismic reflections. In addition, reflection surveys are commonly run in ways that provide information only in the vicinity of a vertical plane that includes a shot and the geophones that record that shot.

The complex velocity structure and heterogeneous nature of near-surface materials tend to make processing and interpretation of shallow data difficult. This is further compounded by the difficulty of coupling the geophones to the ground sufficiently to record high frequencies. Environmental restrictions on shallow seismic sources sometimes prohibit use of high frequency energy.

E. USEFUL ENVIRONMENTAL APPLICATIONS OF SEISMOLOGY

1. Identification of fractures

Fractures are conduits for migration of contaminants. Detection of fractures has been a classic use of seismology for many years. Its use in environmental applications, however, depends on the recording of higher frequencies and broader bandwidths than classical seismic methods. P-wave reflection techniques can detect shallow faults with offsets as little as two meters without difficulty. Likewise, the detection of shallow dissolution collapse features on the scale of a few meters horizontally and vertically is more or less routine.

Detection of joint patterns and strike-slip faults could also be done with seismic methods having better resolution than now commonly available.

As discussed below, we believe that multi-component seismology could be developed further for shallow environmental applications.

2. Locating buried objects and voids

The use of seismology to locate voids and small objects is difficult, and other methods such as magnetics are more cost effective. Any successful use of seismology would be non-standard and could employ cavity acoustic resonance, diffractions, surface waves, and/or phase distortions.

We view this as a very low priority area for research.

3. Mapping bedrock surfaces beneath landfills

Materials within a landfill typically attenuate seismic waves much faster than natural geological materials. It is therefore more difficult to use seismic methods within the landfill than to use them adjacent to the landfill.

There are several approaches that can be taken. The generalized reciprocal method of seismic refraction can be used. Another method that could be applied is undershooting of the landfill by placing the seismic source on one side of the landfill and the receivers (geophones) on the other side. This normally involves wide angle reflections that can have significant phase distortions, making data processing more difficult.

Refraction can also exploit the dry, loose nature of contained landfill materials to effectively enable mapping the lateral boundaries (edges) of individual cells even if mapping the bottom topography of the same cell might prove very difficult.

A vertical or horizontal borehole can also be used to place sources or receivers (geophones or hydrophones) on the edge of the landfill. Traveltime anomalies can then be used to analyze for depth and/or velocity variations in the vicinity of the landfill.

We view this area of research as being of low priority because the techniques are already available but not often implemented because they are non-standard to most practicing seismologists.

F. SOME POTENTIALLY FRUITFUL RESEARCH AREAS

Our highest priority items are discussed below, and the prioritization is shown in Table 1. Some improvements in seismic techniques are within reach in the time frame of one to two years. The first area is shallow seismic sources. The second area is borehole seismology and transposed S-wave VSP. A third area is shallow multi-component seismology.

1. Sources for shallow surface seismic

A two-person portable Vibroseis source has been developed by a student of Dr. Klaus Helbig at the University of Utrecht in The Netherlands. An effort should be made to test this source at some DOE facilities in the US. The frequencies reported at the 1989 Society of Exploration Geophysicists convention were in the range of several hundred hertz, although it should be noted the data were collected on a tidal flat that is known to be one of the most favorable recording sites in the world. The combination of low cost, portability, high frequency, and environmental tolerance make this an extremely attractive source.

In the mid 1970s the MiniSOSIE technique was briefly in vogue for shallow reflection work in the US. The technique uses real-time autocorrelation stack processing in the recording truck to sum the signals from 1000 to 2000 impacts from civil engineering earth compactors at each "shotpoint". The only equipment on the market uses technology from before 1976. The faster microprocessors that have evolved in the past 15 years would allow faster processing in the recording truck which could allow smaller sources with higher frequencies to be used for MiniSOSIE recording. The feasibility of using a more modern version of this and/or other pulse-coded recording techniques should be examined. The technique is very desirable because of its tolerance for large amounts of cultural noise and low environmental impact.

To assist in the rapid and effective development of multi-component seismology (Item 3), hardy, consistent, and wide-band surface shear wave seismic sources will also be required.

2. Borehole seismology and transposed S-wave VSP

Seismic methods attain higher resolution when either the source or receiver or both are placed in boreholes. Wavelengths used in borehole seismology are typically in the range of 1/10 to 1/40 those used in surface seismic methods. While resolution improves approximately linearly with decreasing wavelength, the question of resolution in borehole seismology is more complicated than for surface reflection methods.

In many cases, boreholes are available adjacent to DOE waste sites. These could be used to examine the mechanical properties within the environmentally sensitive areas without further drilling if a suitable source were available that did not permanently damage the boreholes. The possibility of adapting borehole sources to smaller shallow boreholes should be studied. Smaller versions of sparkers (i.e., sources of acoustic energy) and other sources should be developed, and the possibility of using piezoelectric technology for both P-wave and S-wave apparatus should be examined in both clamped and unclamped modes of operation. When this is done the borehole seismology field breaks naturally into the following divisions: nine component VSP, nine component transposed VSP, and nine component crosshole tomographic surveys. These are not all at the same level of technical development. The areas requiring research and development are listed below.

Nine Component VSP

This is a powerful technique for the location of S-wave anisotropy at depth and as a function of depth. In fact it is probably the only technique (with a surface source) that can identify fracture zones at different depths. In this technique the seismic source is placed on the surface and a three component receiver is placed in the borehole. The receivers exist but small high frequency S-wave sources need to be developed. In addition the state-of-the-practice in data handling, data processing, analysis, and interpretation lags behind the state-of-the-art. The same is true for fully elastic modeling and inversion.

Nine-Component Transposed VSP

Here the seismic source is placed in the borehole and the receivers are placed in the borehole. This requires development of the proper downhole source but it offers the possibility of wide ranging, rapid data acquisition. However, no nine-component downhole source exists at this time. The modeling, inversion, and analysis theory does exist but again it is not commonly used.

Nine-Component Cross Hole Tomography

This technique offers the highest resolution and highest information content of all seismic techniques but provides information only for the section between pairs of boreholes. Again the proper nine component downhole source does not exist. Subsets of this method exist. Compressional wave (P-wave) tomography is highly advanced and theoretical efforts are underway to use more than just the first arrival times. Furthermore, statements of resolution and errors of the image are not fully available at this time.

In the full nine component form of cross hole tomography the proper data handling, data processing, full waveform inversion, and interpretation techniques do not exist even at the theoretical level. Fully elastic modeling of anisotropic media exists as does modeling of statistically described media. This is important because as the seismic frequencies rise the effects of scattering have to be understood as well as the effects of anisotropy. This topic is given the highest level of long-term priority by this committee.

If small borehole seismic sources can be made strong enough to send usable signals to the surface from 20 meters depth, some useful applications of S-wave tomography and transposed VSP could rapidly evolve. Sources smaller in diameter and in length are needed. The possibility of putting such a source into horizontal boreholes beneath a waste site is especially attractive.

If the smaller source tools are successfully developed, a more efficient full-waveform tomographic inversion algorithm for S-waves would be needed.

3. Multi-component seismology

Recent advances in the use of multi-component seismology by major oil companies could be adapted for use in environmental problems. Azimuthal refraction analyses of S-waves can be used to detect fractures. Also, decreases in P-wave refraction velocities using the generalized reciprocal method can be an indicator of fractured bedrock beneath alluvium or other low-velocity material. S-wave birefringence could be used for analysis of crack azimuth/density. The committee views this as a high priority area for research in the 3 to 5 year time frame.

TABLE 1. Ranking of research priorities

Research Topic	1–2 yr rank	3–5 yr rank
Shallow seismic sources:		
P & S wave, surface and borehole	1	–
Use of horizontal boreholes under sites		
and transposed VSP	–	3
Fracture detection/location, surface methods	2	2
S-wave tomography, borehole 9-component	3	1

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7 GRAVITY AND MAGNETICS*

Gravity: Chapter Summary

Gravity methods have difficulties in detecting small objects like containers, and even large contaminant plumes when the plume density varies little from the surrounding ground water. In specific cases gravity can be diagnostic. For example, at Idaho National Engineering Laboratory, impoundments of water are periodically released to the subsurface and then gravity measurements are used to trace the passage of the water through the vadose zone, thus displaying the heterogeneous flow paths or contaminant migration.

Short Term (1–2 years)	Long Term (3–5 years)
None	(1) Develop improved, rapidly deployable gravimetric instruments with sensitivities as low as 10 microgals.

Magnetics: Chapter Summary

Magnetic methods are well developed for detecting metal objects and are easily deployed for rapid reconaissance. Development priorites are:

Short Term (1–2 years)	Long Term (3–5 years)
(1) Improve forward modeling including demagnetization and residual magnetization effects as well as magnetic field disturbance due to containers. Improve inversion techniques.	(1) Develop improved tensor magnetic gradiometers. (2) Investigate use of magnetic polymers for tracing fluid flow.

A. GRAVITY

Gravity methods can be thought of as passive in that they emit no form of energy as a probe, but simply measure the earth's ambient gravity field and areal distortions in that field caused by density variations of rocks, natural structures, or artifacts containing materials of differing density. The measured gravity variations are interpreted in terms of probable subsurface mass distribution, which are the basis for inferences about geologic conditions or the presence of human perturbations of the environment (e.g., buried trenches, buried objects).

The successful use of gravity for geologic mapping by the minerals and petroleum industries is well documented. Over the years these applications, as well as engineering and archaeological applications, have required increasingly higher measurement sensitivity for more accurate, less ambiguous interpretation. This need led to the evolution of the branch of the gravity method called "microgravity." It is microgravity that has the potential to be of great value in the area of characterization of environmental resotoration sites; however, this potential has not been systematically evaluated to our knowledge. We, therefore, make the following recommendation:

- DOE needs a 1-year systematic evaluation based on the literature of gravity applications to EM problems.

Key research areas that may result from this evaluation include:

1) Improve gravimetry for rapid, cost-effective acquisi-

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tion of high-sensitivity (<10 microgal) data for subsurface detection and mapping (e.g., trench boundaries, buried objects).

2) Fluid-flow monitoring.

Key advantage: Useful in areas of cultural noise that severly restricts other methods.

B. MAGNETICS

The surface magnetic method of non-intrusive characterization involves measurements (using a "magnetometer") of the direction, gradient(s) and/or intensity of the Earth's magnetic field and interpretation of variations in these quantities over the area of investigation. These variations are called magnetic anomalies and may be of two types. Induced anomalies are the result of magnetization induced in a body by the Earth's magnetic field, and remanent anomalies are the result of permanent magnetization of a body. Most magnetic anomalies are a combination of the two types, but for the environmental restoration application of detection and location of buried ferromagnetic objects (e.g., drums, tanks, scrap metal) the remanent anomaly usually will dominate. Magnetic susceptibility of a geologic material is proportional primarily to its content of iron-bearing minerals, principally magnetite, the most abundant magnetic mineral in the earth. Sedimentary rocks generally have very small magnetic susceptibility compared with igneous or metamorphic rocks, which tend to have higher magnetite content.

In the minerals and petroleum industries, the magnetics method has been used with great success to map geologic structure quantitatively. In the area of environmental restoration, the method has also been quite successful in providing indications of ferromagnetic objects by the presence of an anomaly. However, quantitative interpretations (3-D location and geometry of ferromagnetic objects) have not been commonly employed in environmental restoration projects. This is due partly to the lack of a practical magnetometer that measures magnetic field components simultaneously and to the difficulty of quantitative interpretation when permanent magnetization and demagnetization (a complex reduction in effective magnetization of a body when it has relatively high values of permanent magnetization) are present; this latter situation is very common in the characterization of environmental restoration sites involving buried ferromagnetic objects. These impediments are solvable and the above discussion has led us to make the following recommendations to improve the applicability of the magnetics method to solving environmental restoration problems:

Priority 1: Forward modeling to include:

a. Demagnetization, permanent magnetization, and multi-components (total and gradient fields). 1 yr.

b. Inversion, 1 yr.

c. Statistical evauation of results to satisy QA/regulator requirements. 1yr.

Priority 2: Development/implementation of a state-of-the-practice tensor magnetic gradiometer. Fully operational, ruggedized, with QA procedures.

a. Instrumentation. 3 yrs.

b. Interpretation. 2 yrs.

Other areas not prioritized:

Fluid-flow tracers, magnetic field/susceptibility logging, stratigraphy, and chemical and biological alteration.

8 TECHNIQUES VS GENERIC SITE CHARACTERIZATION OBJECTIVES

A. INTRODUCTION

In the second stage of the workshop, participants divided into four "crosscutting" groups and considered the performance of all technologies in accomplishing three tasks common to most environmental restoration sites

(1) detection of objects, such as drums, buried at shallow depths (< 10 m),

(2) description and characterization of an area's local subsurface geology and hydrology, including such properties as stratigraphy, fracture extent and frequency, porosity, permeability, and water saturation, etc., and

(3) identification and tracing of plumes of pollutants in the subsurface.

The groups' purpose was to identify areas of research and development that would allow the technologies to perform these tasks better. Most groups began by screening technologies as to their suitability for performing each of the three tasks. For example, gravity methods have no application to locating small buried objects, and so no research was indicated for gravity in this task area. Then a variety of approaches were taken by the groups, to identify key research areas for the applicable technologies. We have combined their approaches into three summary tables, one for each of the three generic categories listed above.

B. SHALLOW OBJECT DETECTION

1. Technology Assessment

GPR

This technique is effective in mapping the detail of a buried waste site but only in resistive media and hence may be severely limited by specific site characteristics. It should not be used for general reconnaissance, but for evaluating the specific details of interest, as identified by other methods.

Seismology

The utility of seismic methods for this problem is limited at this time because the source and receiver ground coupling and attenuation problems are severe. Also, high resolution seismic depends on developing better higher-frequency sources than exist at the present time.

Gravity

No application.

Complex Resistivity

Little or no applicability, unless reactive materials are sought.

Magnetics

The magnetic methods provide a good resource for performing reconnaissance surveys as a result of ease of use and deployment. The technique is limited to identification and coarse location of magnetic objects.

Electromagnetic/Induction Methods

These techniques measure conductivity differences, but are limited in both lateral and depth resolution.

2. Investigation Strategy

A strategy for locating buried objects would begin with a combined magnetic and EM/Induction survey. Based on the results of these surveys the electromagnetic site characteristics can be used to determine the viability of GPR. Provided it makes sense in terms of the local geology, GPR techniques can then be used to perform a much higher resolution analysis of specific areas of interest.

3. Research Priorities

The research areas with greatest potential for return are considered to be in forward and inverse modeling efforts in EM/Induction and Magnetics.

Another priority would be alleviating the clutter problem in EM and GPR methods. The noise problem was cited by one group as being the biggest obstacle to geophysical object detection at DOE sites. "Finding drums in the middle of an open field is trivial, but how do you find [them] on a site with power lines overhead, utility lines underground, and traffic all around?"

Improving radar antenna design and processing of data would improve GPR capability for object detection.

Two groups cited appropriate data fusion, though perhaps not a technology in the usual sense, as the highest priority for improving our ability to locate buried objects.

One group thought high frequency seismic and tomography would be useful, but seismic was scored very low in this task by the other groups.

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B. GEOLOGIC AND HYDROLOGIC CHARACTERIZATION

1. Technology Assessment

GPR

GPR provides higher spatial resolution when compared with all other techniques, but as the depth of penetration is very dependant on specific site characteristics its applicability is not always assured. The method will consistently be more useful in detecting shallow rather than deep targets.

Seismic

Seismic techniques allow deeper investigation than GPR with fewer site limitations, but the resolution of these techniques is much lower than that available from GPR.

Complex resistivity

This technique may be useful, in mapping chemical reactivity, but the same physical information, in part, is available from other EM techniques at a much lower cost

Gravity

Gravity methods may offer some capability in certain circumstances, but the utility will be limited by the resolution and by the time and expense of running comprehensive surveys.

Magnetics

Magnetics are probably not applicable except in unusual cases such as magnetite deposits at the bottom of buried stream channels or strongly magnetic basement rocks.

EM/Induction

The resolution is limited, however it will be better in shallow situations. For the deeper locations DC resistivity will most likely be more appropriate.

DC resistivity

Again, like the EM/Induction technique, resolution is limited. These techniques, however, offer the potential of looking much deeper.

2. Site Investigation Strategy

The approach to site analysis for geological and hydrological characterization was divided by one group into two cases: deep characterization (> 30 m), and shallow characterization (< 30). The ranking of technologies for use in these two regimes was slightly different in terms of the mode of first choice. In the case of shallow geologic and hydrologic characterization a survey would start with a combined EM/Induction and DC resistivity survey. The results of this survey would then be used to determine whether seismic or GPR techniques would be most appropriate for a further characterization. The other techniques are probably not applicable to this task.

For a deeper site characterization, seismic and DC resistivity methods would be used to perform the initial site analysis. The results of this would provide some insight as to the usefulness of EM/Induction techniques. For this case gravity may offer some utility especially when combined with the seismic data. If the data indicate that it is appropriate, one might consider complex resistivity. This is, however, only useful where chemical heterogeneity is important.

3. Research priorities

The highest research priority should be directed towards methods to describe and quantify geological heterogeneity, such as by improving seismic capabilities in the areas of seismic sources and in the relation between seismic and hydrologic parameters.

Another priority would be in improving 3-D display and analysis of EM/Induction and DC resistivity data. This may be thought of as a subset of data fusion.

Improvements in instrumentation, in cost, ease of use and capability would also provide a significant pay-off in terms of being able to quickly make multiple measurements.

D. PLUME TRACING

1. Technology Assessment.

GPR

GPR has great promise for locating subsurface, nonaqueous-phase liquids.

Seismic

These techniques have limited applicability except in special cases such as monitoring leaching or steam/fire flood fronts. It may offer some use in monitoring processes such as *in situ* vitrification.

Complex resistivity

This can be of use, but it requires secondary reactions to provide information not better obtained by othe techniques. In certain cases it may offer significant information about organics, but requires further research to understand the reactions involved.

Gravity

Little or no applicability.

Magnetics

Little or no applicability.

EM/Induction

This technique will work well for conductive plumes, but has only limited applications to organic plumes.

DC resistivity

This technique offers the opportunity to monitor nonconductive plumes, but it requires a significant resistivity contrast between the plume and the host medium. This contrast will probably not be realized for the concentration levels typical of a DOE waste site.

Self Potential

This technique is very poorly understood at this time, but it may offer a significant capability for monitoring changes associated with plume propagation, provided that the background problems can be solved. Additional research to understand the physics of this process would be useful.

2. Site Investigation Strategy

Surveying plumes would start with EM/Induction techniques followed by DC resistivity and GPR methods. The other techniques are of much more limited utility but as indicated would be applied in the order of seismic, SP and possibly gravity.

3. Research priorities

Research efforts should concentrate on improving the understanding of complex resistivity's relation to secondary reactions of contaminants.

Additional work in both GPR and EM/Induction are followed by work in SP and seismic respectively, in order of potential payoff.

Research should be encouraged in image processing (a subtopic under processing techniques and data fusion).

Research into different source-receiver configurations that might be used for EM focused beam steering or to enhance mapping, should be a priority.

E. GENERIC RESEARCH AREAS

A generic set of research priorities, independent of the three cases considered above (object location, geologic description, and plume identification), was identified and is presented here with no attached priorities. There is also a significant amount of overlap among the different areas.

1. The problem of identification and interpretation of shallow nonconductors in a dense environment.
2. The identification of measurable physical characteristics of organic materials and plumes.
3. Improvements in the quantification of geophysical information as it pertains to shallow buried objects.
4. Evaluating innovative borehole techniques using any methods that may be used for specific object identification. A specific example to provide illustration would be to locate an object via some technique discussed above, say magnetics, then drill a small borehole close to the object and use some advanced borehole method (e.g. neutron activation to provide further information regarding the object.

F. SUMMARY TABLES

In the following three summary tables we have ranked research needs by geophysical technology for each of the three generic tasks considered above. To do this we considered first the stage of development of each technology regarding its ability to carry out the needed task. Stages of development were indicated by three categories, High, (H), meaning the technology was maturely developed, Medium, (M), and L (L), meaning the technology was in an early stage of evolution and that much future development was possible and promising. Next, we considered the overall utility of the technology in performing the task at hand, using (H) to indicate greater utility and (L) showing no applicability. This is shown in column 3 of the tables below. A qualitative "score" (column 4) was assigned to each technology based on its utility and level of development. Thus, GPR received a high score (H) in Table 1–shallow object identification–because the technology has proven to be useful and yet is still in the early stages of its technological development. This high score for GPR translated into an overall rank of high (H) among 6 technologies considered for research funding directed toward advancing our ability to detect and identify buried objects. The overall rank is shown in the final column of the following tables.

Table 1. Shallow Object Detection: Recommended Research Priority Ranking

Technology	Level of Development	Utility	Score	Overall Rank
Gravity	H	L	L	L
Magnetics	H	M–H	M	M
GPR	L	H	H	H
EM	M	M–H	H	H
Seismic	H	L	L	L

Table 2. Geologic/Hydrologic Parameters: Recommended Research Priority Ranking

Technology	Level of Development	Utility	Score	Overall Rank
Gravity	H	L	L	L
Magnetics	H	L	L	L
GPR	L	M	H	M
EM	M	H	H	H
Seismic	H	H	H	H

Table 3. Plume Tracing: Recommended Research Priority Ranking

Technology	Level of Development	Utility	Score	Overall Rank
Gravity	H	L	L	L
Magnetics	H	L	L	L
GPR	L	M	H	M–H
EM	M	H	H	H
Seismic	H	M	M	M

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APPENDIX B: ACRONYMS USED IN THIS REPORT

CAT	Computerized axial tomography
CW	Continuous wave
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
EM	Electromagnetics
EPA	Environmental Protection Agency
GPR	Ground penetrating radar
GRM	Generalized reciprocal method
IP	Induced polarization
OTA	Office of Technology Assessment
PC	Personal computer
QA	Quality assurance
R&D	Research and Development
RF	Radio frequency
SAR	Synthetic aperture radar
SEG	Society of Exploration Geophysicists
SP	Self potential, (or spontaneous potential)
USGS	United States Geological Survey
VSP	Vertical seismic profiling